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David Taylor Research Center

Bethesda, MD 20084-5000

DTRC/SHD-1324-01 JUNE 1990

SHIP HYDROMECHANICS DEPARTMENT

TECHNICAL REPORT

DTRC/SHD-1324-01 HYDROMECHANICAL STUDY OF A JHU/APL MINISPAR June 1990

HYDROMECHANICAL STUDY OF A JHU/APL MINISPAR

By

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J. H. Hamilton

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1a REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b RESTRICTIVE MARKINGS
2a SECURITY CLASSIFICATION AUTHORITY	3 DISTRIBUTION / AVAILABILITY OF REPORT APPROVED FOR PUBLIC RELEASE DISTRIBUTION UNLIMITED
2b DECLASSIFICATION / DOWNGRADING SCHEDULE	
4 PERFORMING ORGANIZATION REPORT NUMBER(S) DTRC/SHD-1324-01	5 MONITORING ORGANIZATION REPORT NUMBER(S)
6a NAME OF PERFORMING ORGANIZATION Ship Hydromechanics Dept David Taylor Research Center	6b OFFICE SYMBOL (If applicable) 1543
7a NAME OF MONITORING ORGANIZATION	
6c ADDRESS (City, State, and ZIP Code) kBeathesda, MD 20084-5000	7b ADDRESS (City, State, and ZIP Code)
8a NAME OF FUNDING / SPONSORING ORGANIZATION JHU/APL	8b OFFICE SYMBOL (If applicable)
9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER	
8c ADDRESS (City, State, and ZIP Code) Johns Hopkins Road Laurel, Maryland 20810	10 SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO	PROJECT NO	TASK NO	WORK UNIT ACCESSION NO
			DN509171

11 TITLE (Include Security Classification)

HYDROMECHANICAL STUDY OF A JHU/ARL MINISPAR

12 PERSONAL AUTHOR(S)
B.B.Wisler & J.H. Hamilton

13a TYPE OF REPORT	13b TIME COVERED	14 DATE OF REPORT (Year, Month, Day)	15 PAGE COUNT
	FROM ______ TO ______		43

16 SUPPLEMENTARY NOTATION

17 COSATI CODES		
FIELD	GROUP	SUB-GROUP

18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)

Sensor System Housing, BoH Torque Induced Strains, Hydrodynamically Induced Strains. (EDC) ←

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

A prototype Johns Hopkins University/Applied Physics Laboratory Minispar sensor system housing was attached to a simulated grate section and towed at various angles of attack and speeds in a towing basin. This was done to aid JHU/APL in evaluating the attachment hardware for structural strength. Measurements of strains at various locations on the attachment hardware were made along with bolt torques and the forward to aft pressure differential on the model. The hydrodynamically induced strains were less than 400 microstrains. Bolt torque induced strains in excess of 1900 microstrains were measured initially. Modifications of the attachment hardware reduced the bolt torque induced strains to less than 400 microstrains, keeping the total strain below the elastic limit for the structural material of the Minispar framework. Keywords: [illegible] ment/housings; towed bodies; [illegible]; [illegible] tests;

20 DISTRIBUTION / AVAILABILITY OF ABSTRACT	21 ABSTRACT SECURITY CLASSIFICATION
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	UNCLASSIFIED

22a NAME OF RESPONSIBLE INDIVIDUAL	22b TELEPHONE (Include Area Code)	22c OFFICE SYMBOL
B.B. Wisler	(202) 227-1547	1543

DD Form 1473, JUN 86 Previous editions are obsolete SECURITY CLASSIFICATION OF THIS PAGE

S/N 0102-LF-014-6603 UNCLASSIFIED

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ABSTRACT

A prototype JHU/APL Minispar sensor system housing was attached to a simulated grate section and towed at various angles of attack and speeds in a towing basin. This was done to aid JHU/APL in evaluating the attachment hardware for structural strength. Measurements of strains at various locations on the attachment hardware were made along with bolt torques and the forward to aft pressure differential on the model. The hydrodynamically induced strains were less than 400 microstrains. Bolt torque induced strains in excess of 1900 microstrains were measured initially. Modifications of the attachment hardware reduced the bolt torque induced strains to less than 400 microstrains, keeping the total strain below the elastic limit for the structural material of the Minispar framework.

ADMINISTRATIVE INFORMATION

This work was performed at the request of the Johns Hopkins University Applied Physics Laboratory (JHU/APL). Center funding was provided by JHU/APL Checks no. 776816 and 791402 of 10 February and 12 July 1989 in accordance with Letter Agreement 511522-0 supported under Navy Contract N00039-87-C-5301.

INTRODUCTION

The David Taylor Research Center (DTRC) was requested by the Johns Hopkins University Applied Physics Laboratory (JHU/APL) to conduct a hydromechanical study of a JHU/APL Minispar. This Minispar is the mechanical housing for a sensor system being developed by JHU/APL. The Minispar is to be attached to an existing grate by Navy divers.

A prototype Minispar and attachment hardware were provided to DTRC by JHU/APL. DTRC then applied waterproofed strain gages to the Minispar hardware at locations specified by JHU/APL. Experiments were carried out using DTRC Carriage 5 in the High Speed Basin and measurements were made of strains at 16 locations on the Minispar and of pressures at 2 tap locations for various angles of attack and flow velocities. The Minispar angle (0, +10, -10, and +90 deg) and Minispar configuration were varied for carriage speeds of 5, 10, 15, 20, 25, 30, and 35 knots (2.6, 5.1, 7.7, 10.3, 12.9, 15.4, and 18.0 m/s).

Additionally, two "dry" tests were performed. One was a torque test that was performed as the Minispar was being assembled. Measurements of strain levels were made as the assembly bolts were tightened. The second, a mechanical pull test, was performed after the towing basin tests were completed. During the pull test, measurements of strain levels and pulling force were made as the Minispar was pulled with a bridle and spring scale apparatus.

The objectives of the towing and the torque tests were to measure the hydrodynamically-induced and bolt-torque-induced strains on the Minispar structure and to provide data for comparison with predictions obtained by JHU/APL using finite element analysis. The JHU/APL strain predictions were derived from potential flow calculations of the pressure distribution on the Minispar surface done at DTRC*.

The objective of the towing basin test series at a 90-deg angle of attack was to determine if the attachment hardware was capable of withstanding a 1750 lb (7784 N) drag force. This drag force was determined by JHU/APL to be the equivalent force on the Minispar that would be produced by a wave slap generating a 7 lb/in^2 (48.3 kPa) pressure differential from one side of the Minispar to the other. The ability to withstand a 7 lb/in.^{2} wave slap is a Naval Sea Systems Command criterion. Calculations were done at DTRC to predict, from forward-to-aft differential pressure measurements,

* Unpublished calculation by H. Cheng and R.W. Miller of Code 1843, August, 1989.

the carriage speed required to achieve a 1750 lb drag on the Minispar*. The objective of the pull test was to verify, by observing the strains on the Minispar structure produced by known loads, that indeed 1750 lb of drag had been achieved during the carriage test at the predicted carriage speed.

This report describes the Minispar and the two configurations tested; describes the three tests performed; and presents a tabulation of the measured data including strains and pressures for a range of attack angles and speeds.

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* Unpublished calculation by D. Coder (of Code 1543), H. Cheng, and R.W. Miller (of Code 1843), September 1989.

DESCRIPTION OF CONFIGURATIONS TESTED

Fig. 1 is a side view of Configuration 1 of the assembled Minispar attached to the grate section. Fig. 2 contains labeled assembly pictures of Configuration 2.

The structure of the Minispar was made of Nitronic stainless steel with a dummy wooden instrument can installed. Two fiberglass skirts were attached to the sides. The assemblea Minispar was 36 in. (91.4 cm) long, 8 in. (20.3 cm) wide and 6.5 in. (16.5 cm) high. The attachment "legs" and "strongback" were made of Nitronic stainless steel for Configuration 2. An aluminum strongback was used in Configuration 1 while the Nitronic strongback was being readied.

The configurations differed in that Configuration 2 had 3/16 in. (0.48 cm) aluminum spacers installed between the strongback and the top of the legs and 1/8 in. (0.32 cm) rubber strips installed between the strongback and the grate edges. Additionally, Configuration 2 had each leg turned 180 deg on the Minispar plate.

TEST APPARATUS AND PROCEDURE FOR THE LABORATORY TORQUE TEST

The torque test was conducted in the DTRC Naval Hydromechanics Division Laboratory adjacent to the High Speed Towing Basin. Both Configurations 1 and 2 were tested. For this test, each of the 2 configurations was attached to the aluminum grate simulation section. Using a dial torque wrench, bolts were tightened to attach the Minispar to the grate section. Strain levels on the 16 strain gages and applied values of torque were collected for various conditions: (1) before tightening any bolts, (2) after torquing the Minispar plate-to-leg bolts, (3) after torquing the leg-to-grate side bolts, and (4) after torquing the strongback-to-leg bolts.

An Acurex MDAS 7000 signal conditioning and data collection system (shown in Fig. 3) was used to collect and organize the data. The salient features of this system are listed in Appendix A. The strain measurement channels were single active-arm 350 ohm bridges with dummy resistors for temperature compensation (see references 1 and 2) mounted inside the Minispar on a separate piece of Nitronic steel. The rest of each bridge was completed on cards in the Acurex system. A computer-switched shunt resistor of 349,650 ohms value was used prior to each data collection to simulate load and set up the ratio of volts to engineering units (EU/V) for each channel (see reference 3). Appendix B contains a calculation of the shunt calibration equivalent strain. Appendix C contains a calculation of the approximate sensitivity in EU/V for the strain channels. Zeroes were subtracted prior to each data collection and a file of zeroes was kept as an aid in detecting bad gages. Before the torque tests were begun, a primary sensitivity checking device was developed. This was done to instill confidence in the strain values measured when the assembly bolts were torqued down. This device is shown at the lower left of Fig. 3. It is simply a strain gage mounted on a strip of aluminum with a "dummy" or bridge completion resistor attached. Fig. 4 diagrams the test setup and calculations made for the checking device. Table 1 contains an instrumentation channel lineup. The matrix of da a from the torque test is given in Appendix D.

TEST APPARATUS AND PROCEDURE

FOR THE CARRIAGE TEST

The test was conducted on DTRC Carriage 5 in the High Speed Towing Basin. As in the torque tests, the Minispar was attached to the grate section via the legs and strongback pieces.

The grate section was, in turn, fastened to a round aluminum adapter plate (see Fig. 5) that was cut to fit and be bolted into a recessed hole in the bottom of the Sonar Dome Destruction Bridge (SDDB). The SDDB, which was originally designed for destructive testing of sonar domes, is a towing bridge for Carriage 5 that suspends an 8 ft (2.44 m) wide by 16.5 ft (5.03 m) long flat plate beneath the carriage bay. Prior to drilling the holes that mount the adapter plate to the SDDB, the adapter plate was carefully aligned so the grate section would be parallel with the SDDB mounting pads. This was accomplished with an apparatus consisting of plumb bobs, levels, lengths of angle iron, and clamps. Fig. 6 shows this whole assembly of Minispar, grate section, adapter plate, and the SDDB mounted on a pair of support stands called beach brackets. This assembly was unbolted from the beach brackets and moved by bridge crane to the carriage. It was then attached to the carriage via pads on the sides of the carriage towing bay.

When mounted on the carriage the flat plate of the SDDB was submerged, placing the Minispar approximately 6 in. (15.2 cm) underwater. Water spray from the high speed towing was contained by strategically located sheets of 4 ft (1.22 m) x 8 ft (2.44 m) plywood and a 16 ft (4.88 m) x 24 ft (7.32 m) tarpaulin. Fig. 7 shows the entire assembly mounted in the carriage bay covered and ready to run.

With model angle and model configuration as parameters and with carriage speed as the independent variable, measurements were made of the dependent variables of strains and pressures.

The pressure measurement equipment is shown in Fig. 8. It consisted of a pressure tank to provide either pressurized water or air for bleeding and calibration purposes, a bleed manifold, and a DTRC-manufactured signal conditioner box to power two of the pressure transducers (channels 19, 20). The signal conditioner outputs were routed to the Acurex system A/D. The channel 18 pressure gage utilized the signal conditioning in the Acurex system. Plastic tubes were routed from the bleed manifold down into the Minispar and terminated at the locations shown in Fig. 8. The termination consisted of an 1/8 in. (0.32 cm) NPT fitting inserted into a tapped hole on the inside of the fiberglass skirts. The hole opening size for the flush tap was 1/8 in. This arrangement can be viewed in Fig. 2. The locations of the strain gages are shown in Fig. 9. The matrix of carriage test conditions is shown in Table 2 and the tabulated carriage data are in Appendix E.

TEST APPARATUS AND PROCEDURE FOR MECHANICAL PULL TESTING

This test was conducted beside the High Speed Towing Basin in the East End Fitting Room. The SDDB and attached Minispar were removed from the carriage and set on the beach brackets.

A 40 in. (1.02 m) long section of 1/2 in. (1.27 cm) thick, 6 in. (15.2 cm) by 6 in. aluminum angle beam was attached to the Minispar using the tapped holes that held the fiberglass skirts to the Minispar structure. A wire rope bridle was attached to eyebolts on the ends of the angle beam. A spring scale was inserted in line to a forklift truck which when moved backwards would apply tension to the cable bridle.

Strain values and cable tension were measured while pulling with the apparatus over a range of 0 to 1750 lb of tension. A picture of this arrangement is shown in Fig. 10.

TEST RESULTS AND DISCUSSION

The data obtained from the torque test, the carriage test, and the pull test are tabulated in Appendices D, E, and F, respectively.

The data channels were scanned approximately 3 times per second. At the beginning of each scan, the system clock was interrogated and the time was stored in a buffer. Next, a scan of the data channels was begun. During a scan, 30 samples were collected from each channel at a sampling rate of 10,000 samples per second. An average was calculated for the thirty samples collected at each channel and these averages were stored in a buffer. At the end of the run, the contents of the buffers were written to files on the hard disk. These files were later transferred to floppy disk. Post-test analysis further condensed the data to an overall average value and a standard deviation per channel for each speed run (or carriage pass). This was accomplished by keying all data channels to the speed channel. For a particular run, all data that had speeds within 5% of the target speed were averaged and the standard deviation calculated. These are the values that appear in the Appendices of this report.

The torque test was done to determine how much strain the 16 strain-gaged locations would incur when the Minispar was attached to the grate section.

The data in Appendix D show that Minispar Configuration 1 developed strains of up to 2254 microstrains (1 microstrain equals 1 x 10^{-6} in. of elongation per in. of material) when the strongback bolts were tightened to their maximum of 18 ft-lb (24.4 N-m). Some of the leg strain values were beyond the acceptable 1900 microstrain value for Nitronic stainless steel as shown in Appendix G. A value of 1400 microstrains would allow for additional hydrodynamic strain of up to 500 microstrains before 0.2 per cent yielding occurs at the 1900 microstrain level. The maximum torque that could be applied before exceeding 1400 microstrains was 4 ft-lb (5.42 N-m). In order to achieve a uniform 4 ft-lb on all strongback-to-leg bolts, approximately 12 torquing attempts had to be made. This was because the torquing did not pull the legs into contact with the strongback and therefore torquing one bolt would affect the torque on all others.

Even though Configuration 1 was less than satisfactory, it was decided to begin the carriage test. The carriage test data for Configuration 1 shown in Appendix E consisted of velocity versus strain levels at angles of 0,-10 and +10 deg. The gage locations that picked up the most strain were 1,2,7,8 and 12 (see Fig. 9). Plots are shown in Fig. 11 for these locations versus velocity with fixed angle. Another set of plots is also shown of these channels versus angle with the velocity fixed at 30 knots (15.43 m/s). The plots show that strain values, while exhibiting consistent relationships, did not exceed 175 microstrains for any of the Configuration 1 conditions. It should be noted that the gage at location 5 was not operating for the carriage test. The cable to this gage was damaged during assembly of the Minispar just prior to the carriage test. It was decided not to delay the test for the estimated one and a half days necessary to repair the channel. From Fig. 9, it was determined that gage location 7 should mirror the strain values of gage location 5 and therefore the gage at location 5 was redundant and not needed.

In order to run the 90 deg condition, the SDDB was removed from the carriage and set on the beach brackets. This enabled the adapter plate to be unbolted, rotated 90 deg, and rebolted to the SDDB. Configuration 2 was developed at this juncture. A torque test was performed just as was done for Configuration 1. Using Configuration 2, it was possible to achieve 15 ft-lb (20.3 N-m) of torque on the strongback-to-leg bolts without overstressing the leg strain gages. Only two torquing attempts were necessary to achieve uniform torque because the legs were allowed to contact the strongback through the spacers.

The torque test strain levels in the legs indicate that Configuration 2, with compressible rubber strips as the only contact between the strongback and the grate section, achieved the equivalent strongback clamping force on the grate section that 1 ft-lb (1.36 N-m) would on Configuration 1 (see Fig. 12). By swiveling the legs 180 degrees on the Minispar plate and rebolting them, a more stable configuration in side load was achieved. This was because the side bolts were attached to the grate above the centerline of the Minispar in Configuration 2, whereas in Configuration 1 attachment was made above the side edge of the Minispar.

The carriage test data for Configuration 2 consisted of velocity versus strain at 90 deg only. The gage locations that picked up the most strain were 8,16,1,9 and 3. Plots are shown in Fig. 13 of these strain channels versus velocity. Configuration 2 had additional locations (5,6, and 17) for the strain-gaged Nitronic steel strongback. Pressure measurements (18,19 and 20) were also added for Configuration 2 in an effort to measure drag on the Minispar. The purpose of the pressure measurement was to help determine when 1750 lb (7784 N) of drag was achieved on the Minispar as required by JHU/APL. The force value of 1750 lb is the force that would be achieved if there was a 7 lb/in^2 (48.3 kPa) uniformly distributed pressure differential from one side of the Minispar to the other when towed at 90 degrees. Channel 19 (fwd. pressure) minus channel 20 (aft pressure) should equal the channel 18 (differential pressure) measurement. This can be seen from the pressure graph on Fig. 13. Fig. 14 contains plots of real time data for the 30-knot (15.4 m/s), Configuration 2, carriage test condition. It can be seen that the strains and pressures followed the rise and fall of the carriage speed as would be expected.

When the pull test data (Fig. 15) are compared to the data from the Configuration 2, 90-deg carriage data for selected strain and pressure channels (Fig. 13), it can be seen that 1750 lb on the Minispar was easily exceeded at 27 knots (13.9 m/s). The projected side area of the Minispar is 234 in.^{2} (1509 cm^2). The pressure measurement was made using a single central tap location on each side of the Minispar (see Fig. 8). Therefore an approximation was made in attempting to measure this uniform pressure differential. The actual pressure distribution was such that a 12 lb/in.^{2} (82.7 kPa) differential pressure across the Minispar at the chosen taps achieved strains equivalent to those achieved in the pull test at 1750 pounds of pulling tension.

CONCLUSIONS

1. Minispar Configuration 1 was not acceptable because the strongback-to-leg bolts could only be torqued to about 4 ft-lb before 1400 microstrains at the leg gage locations was reached. This would only allow for an additional 500 microstrains of hydrodynamic loading before the leg metal begins to yield. Additionally, even under laboratory conditions, too many torquing iterations were necessary to achieve a uniform 4 ft-lb (5.4 N-m) on the strongback-to-leg bolts.
2. Minispar Configuration 2 corrected the Configuration 1 defects of low and uneven strongback-to-leg bolt torques, but at the expense of diminished clamping force on the grate.
3. All hydrodynamically induced strains were less than 400 microstrains.
4. Despite the diminished clamping force on the grate, Configuration 2 is capable of withstanding 1750 lb (7784 N) of side force.

RECOMMENDATIONS

The attachment hardware should be redesigned to enable higher grate clamping force. The higher grate clamping force should be achieved without yielding any metal in the attachment hardware or Minispar structure.

ACKNOWLEDGMENTS

This work was performed by the Special Systems Branch of the Ship Hydromechanics Department of DTRC. The authors gratefully acknowledge the contributions of the following DTRC personnel: Dr. David Coder for technical consultations on hydrodynamics, David Coakley for consultations on structural concerns, Henry Strunk for general assistance in pre-test planning, and

Robert Bishop for carefully installing the strain gages that worked well throughout the test.

The authors would also like to acknowledge the fitting room personnel (John Muglia, Bob Frost, Imire Gonda, and Joe Sidotti) for their assistance in the assembly of the test hardware and for carriage operation.

In all phases of the test, the technical participation and direction provided by Mr. Stanley Cooper of JHU/APL was appreciated. Mr. Cooper's participation included observation and consultation on the conduct of the towing basin experiments.

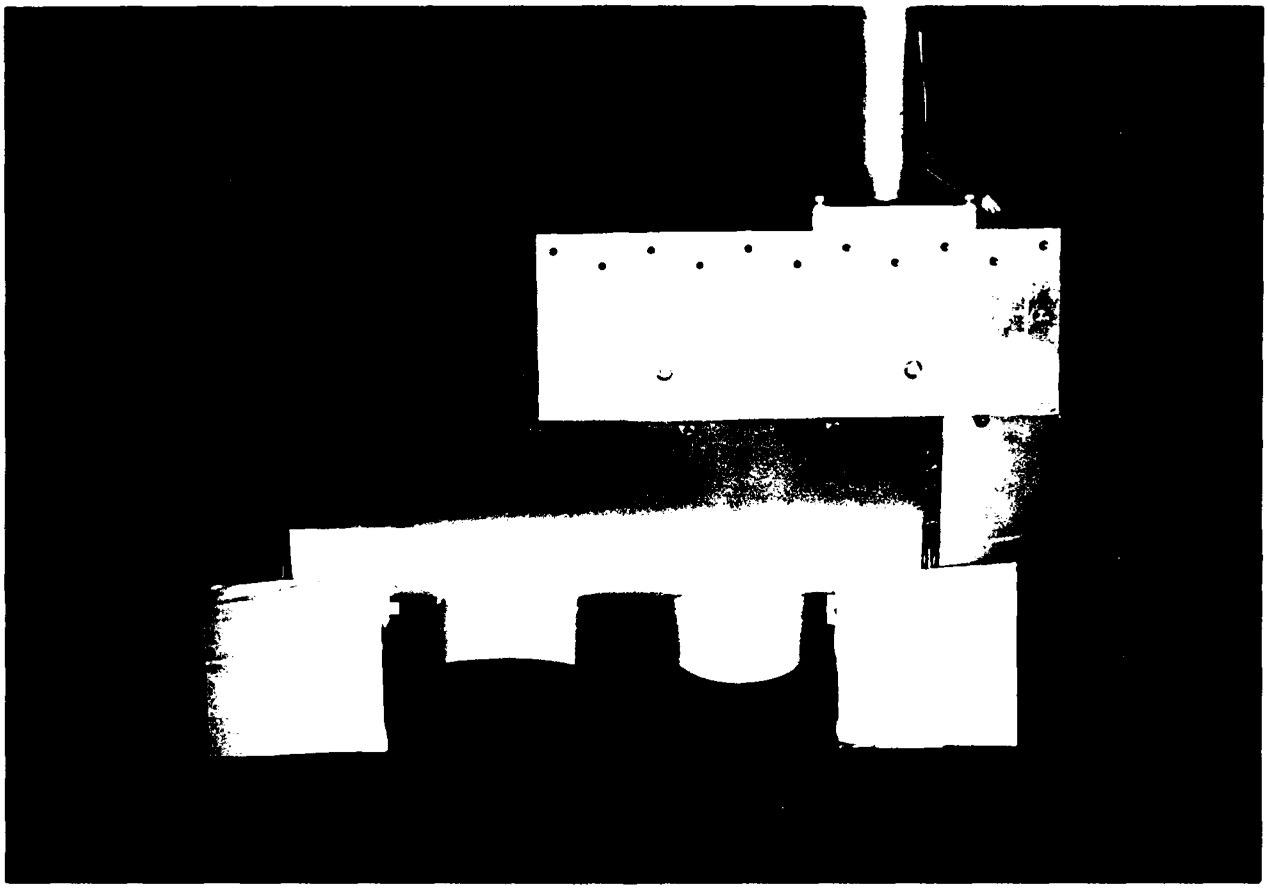


Fig. 1. Minispar Configuration 1 attached to the grate section.

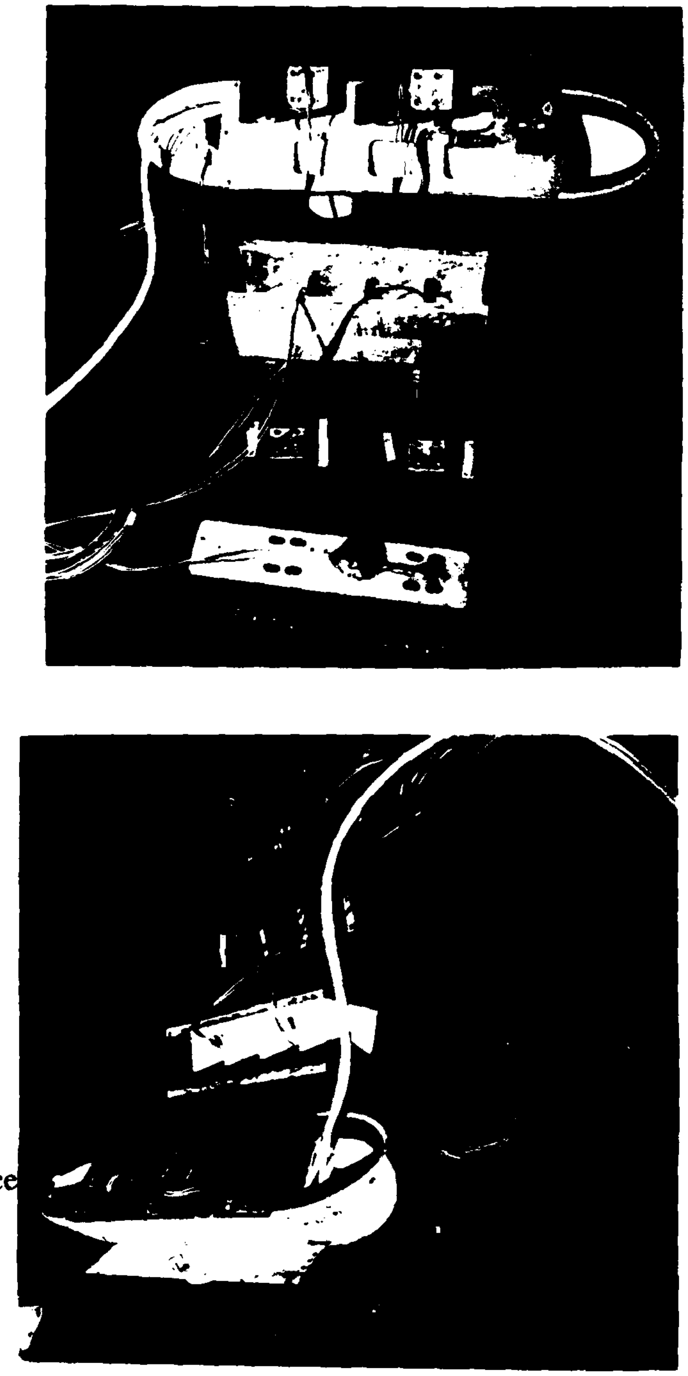
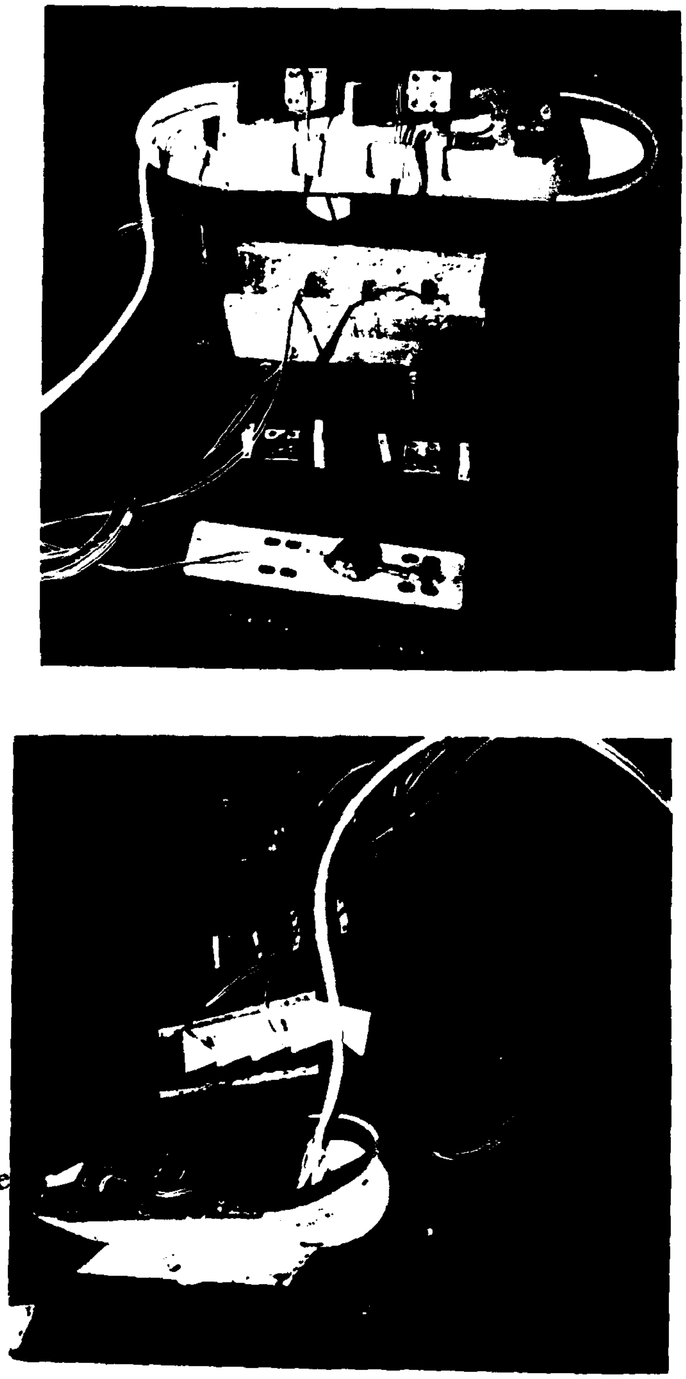


Fig. 2. Assembly pictures of Minispar Configuration 2.



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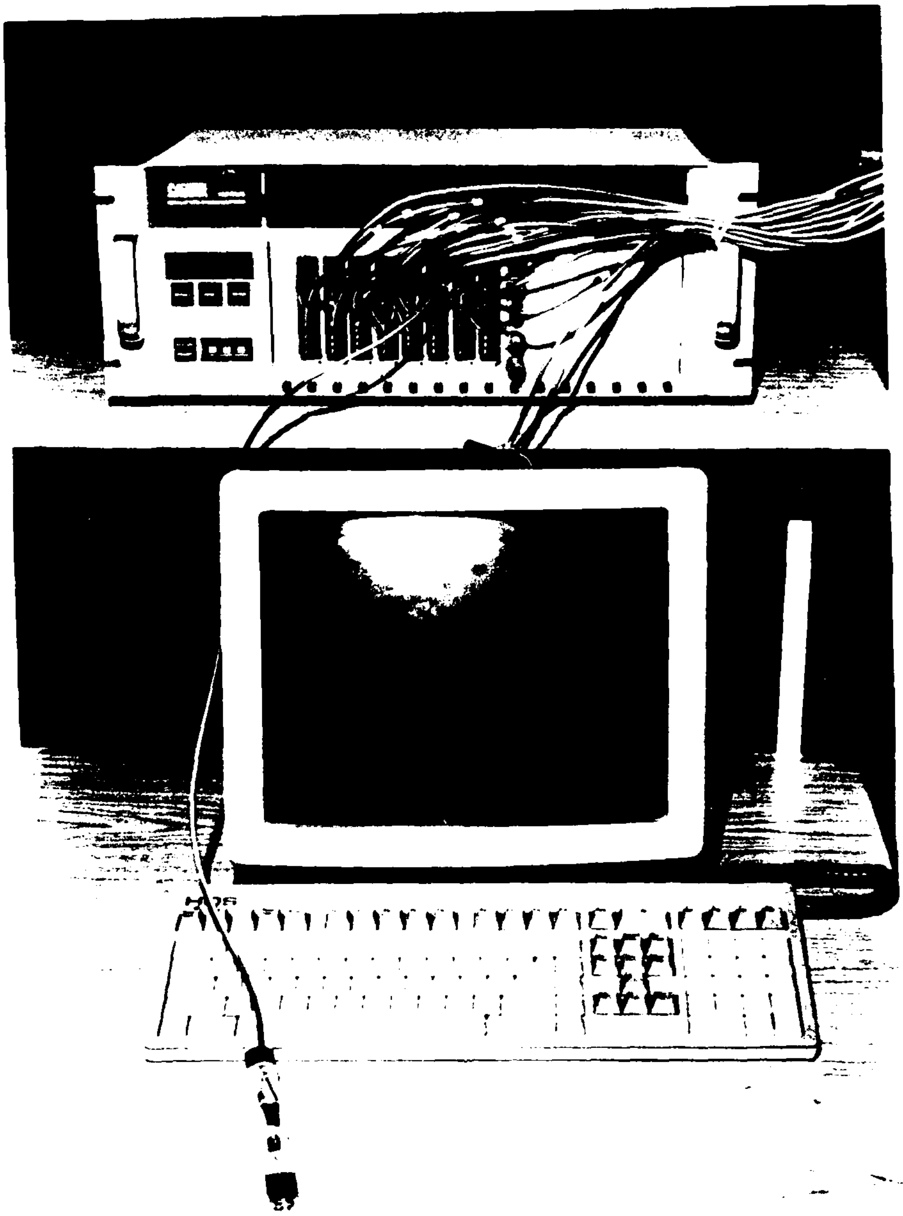
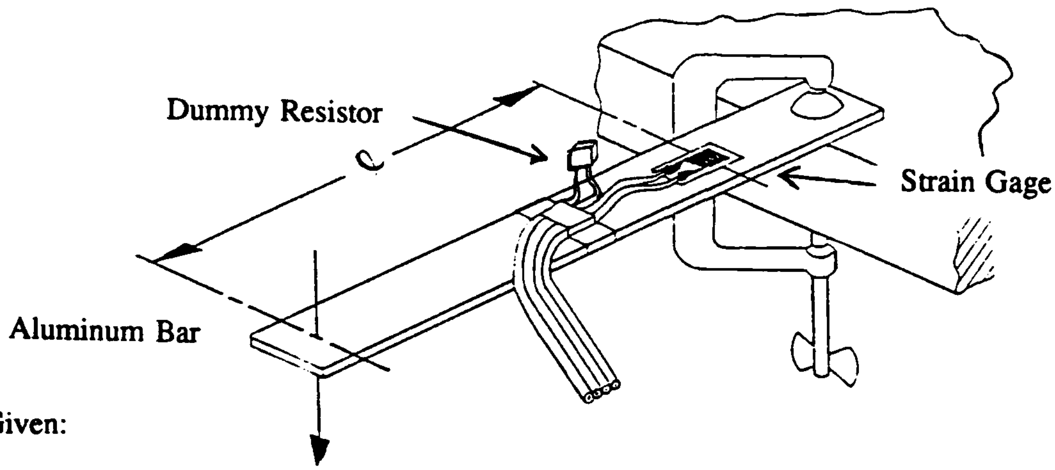


Fig. 3. Acurex MDAS 7000 signal conditioning and data collection system.



Given:

$$\sigma = E * \varepsilon = (M * c) / I$$

$$\varepsilon = (M * c) / (E * I) = (W * l * h / 2) / (E * b * h^3 / 12)$$

$$\varepsilon = (6 * W * l) / (E * b * h^2)$$

σ = stress (psi)

ε = strain (in/in)

E = modulus = $10.6 * 10^6$ (psi) for 2024-T4 aluminum

M = applied moment = W * l (in-lb)

c = distance of surface above neutral axis = h / 2 (in)

I = moment of inertia of rect. beam = $(b * h^3) / 12$ (in^4)

W = weight = 1 (lb.)

l = length = 4.5 (in.)

h = thickness = 0.12 (in.)

b = width = 0.75 (in.)

Then;

$$\varepsilon = (6 * 1 * 4.5) / (10.6 * 0.75 * (0.12)^2) = 235.8 \ \mu in/in$$

Fig. 4. EU/V check out device.

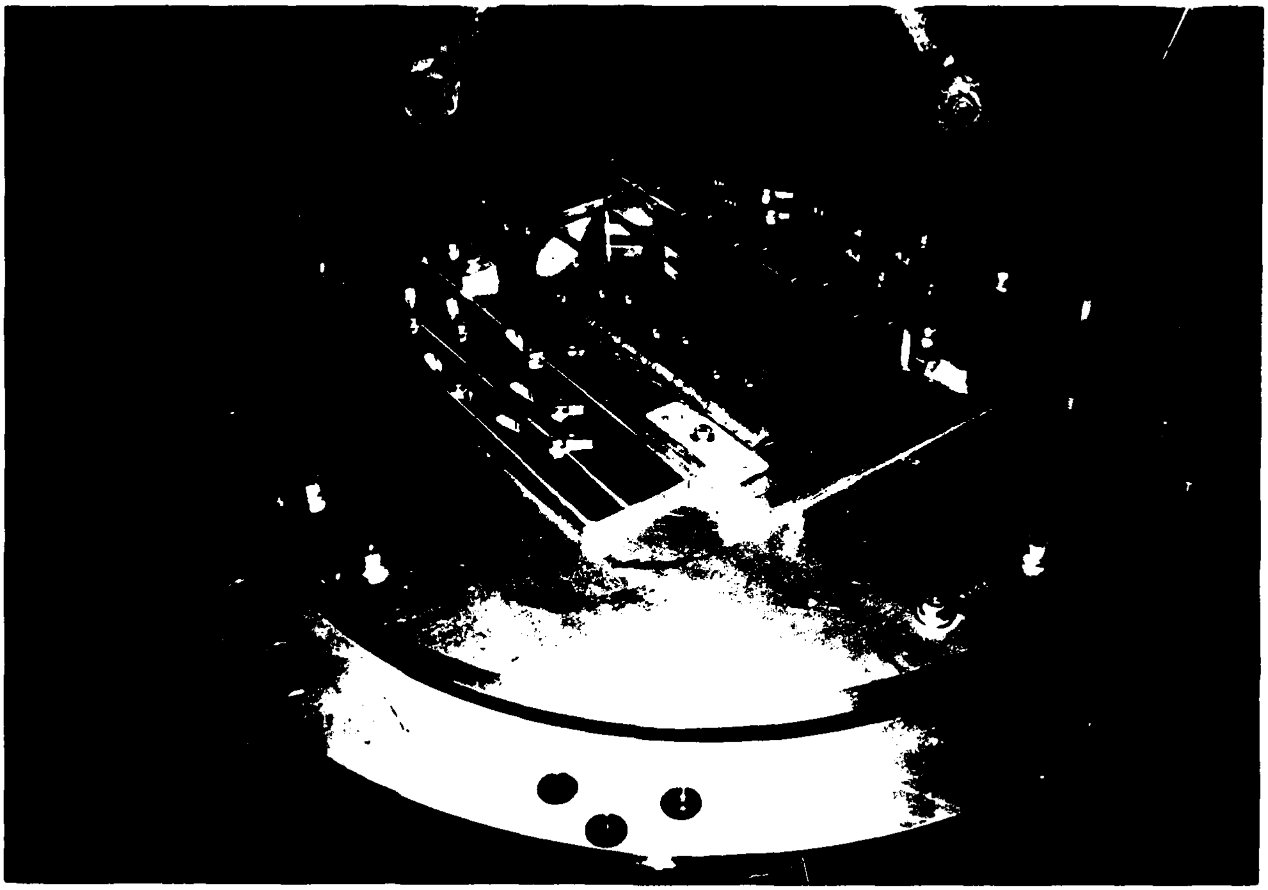


Fig. 5. SDDB Adapter Plate.

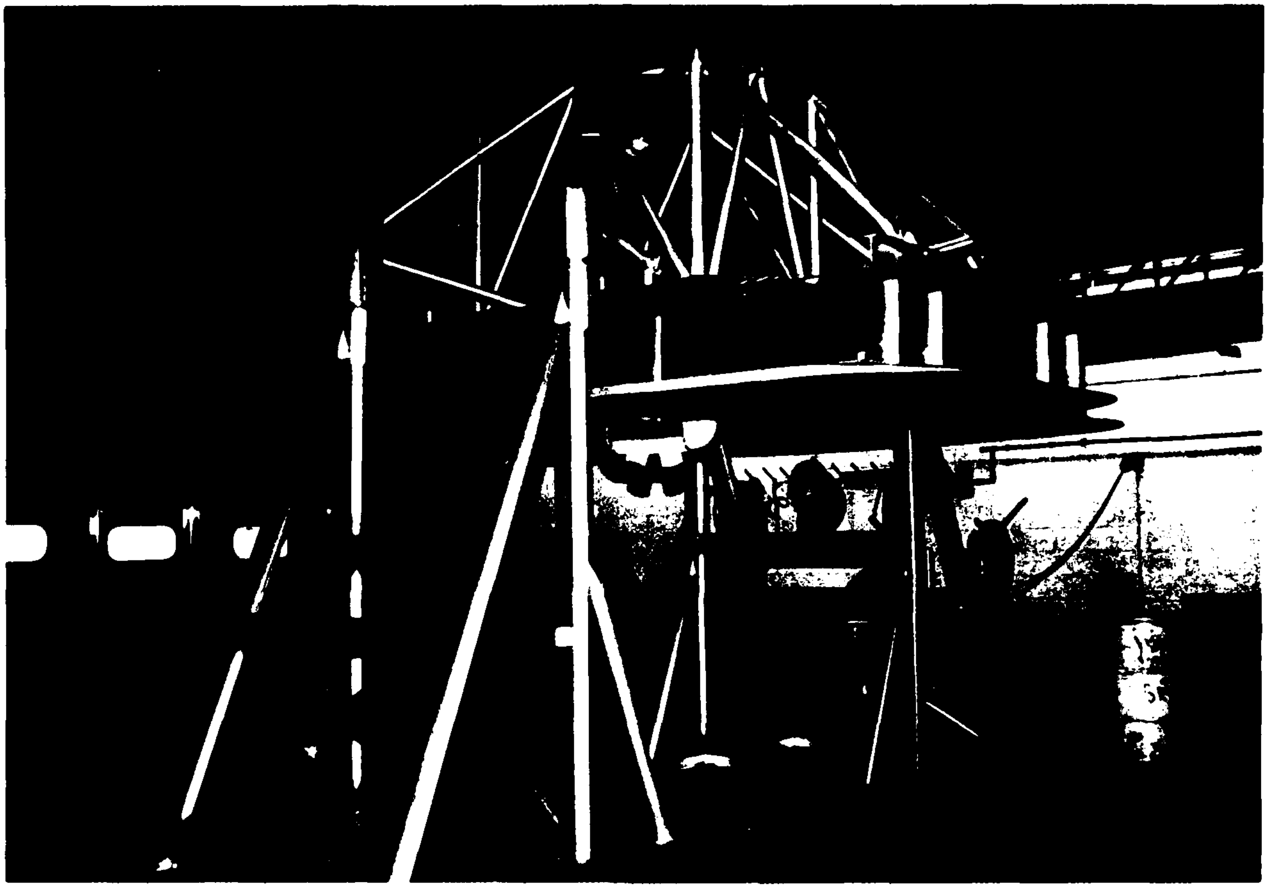


Fig. 6. Assembly of Minispar, grate section, and adapter plate mounted on the SDDB and the beach brackets.

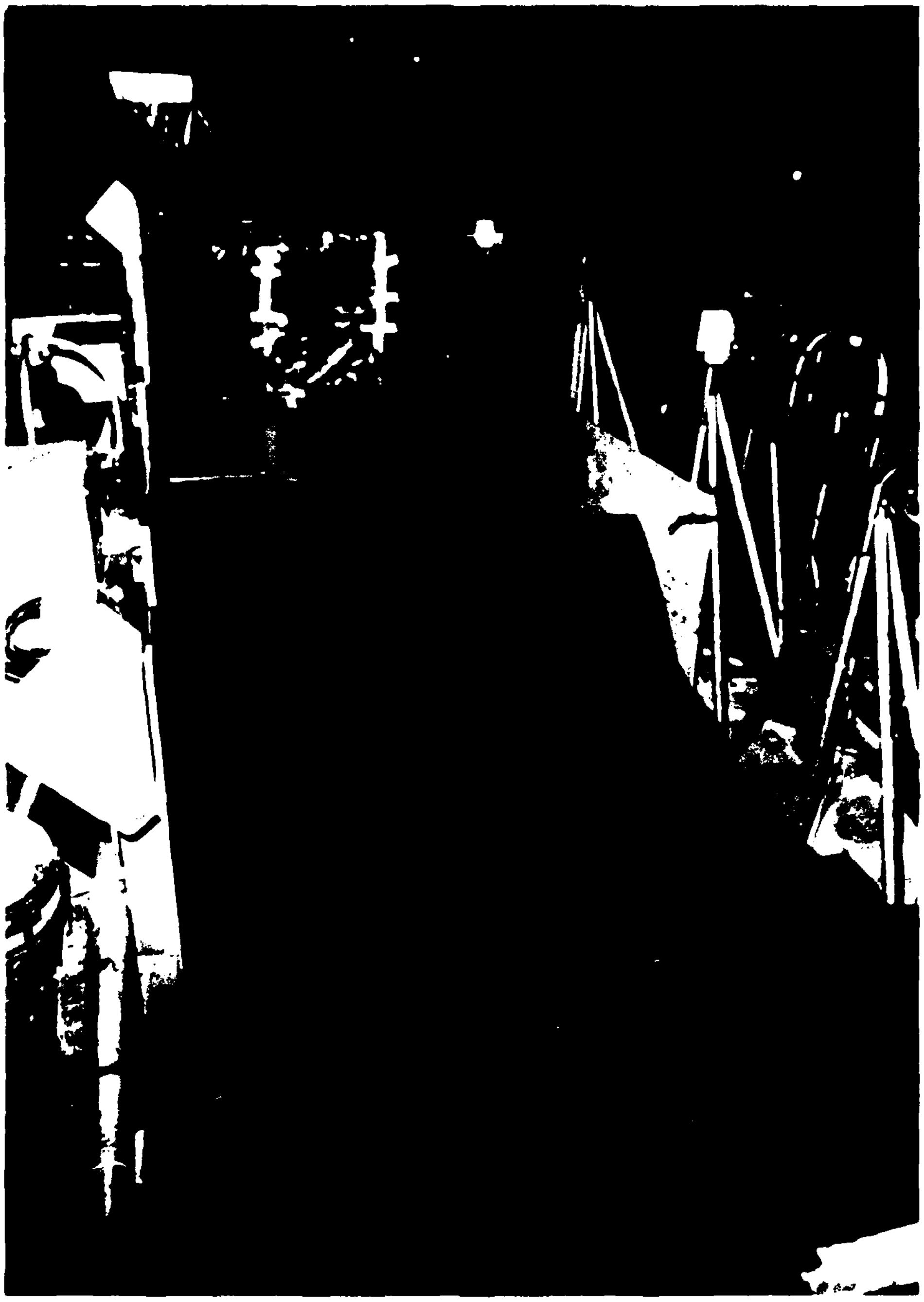
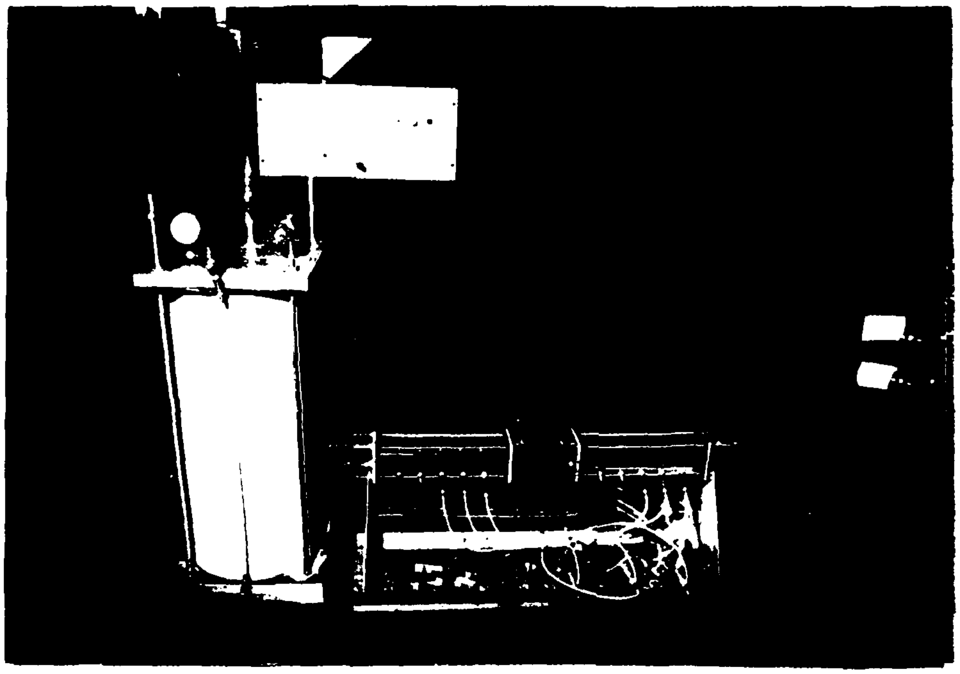


Fig. 7. Entire towing assembly mounted in the carriage bay.



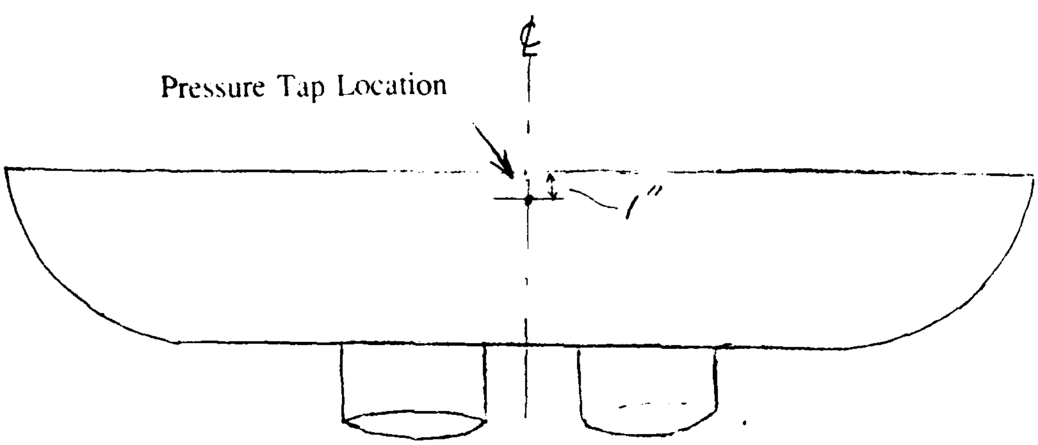


Fig. 8. Picture of pressure measurement equipment and diagram of pressure tap locations.

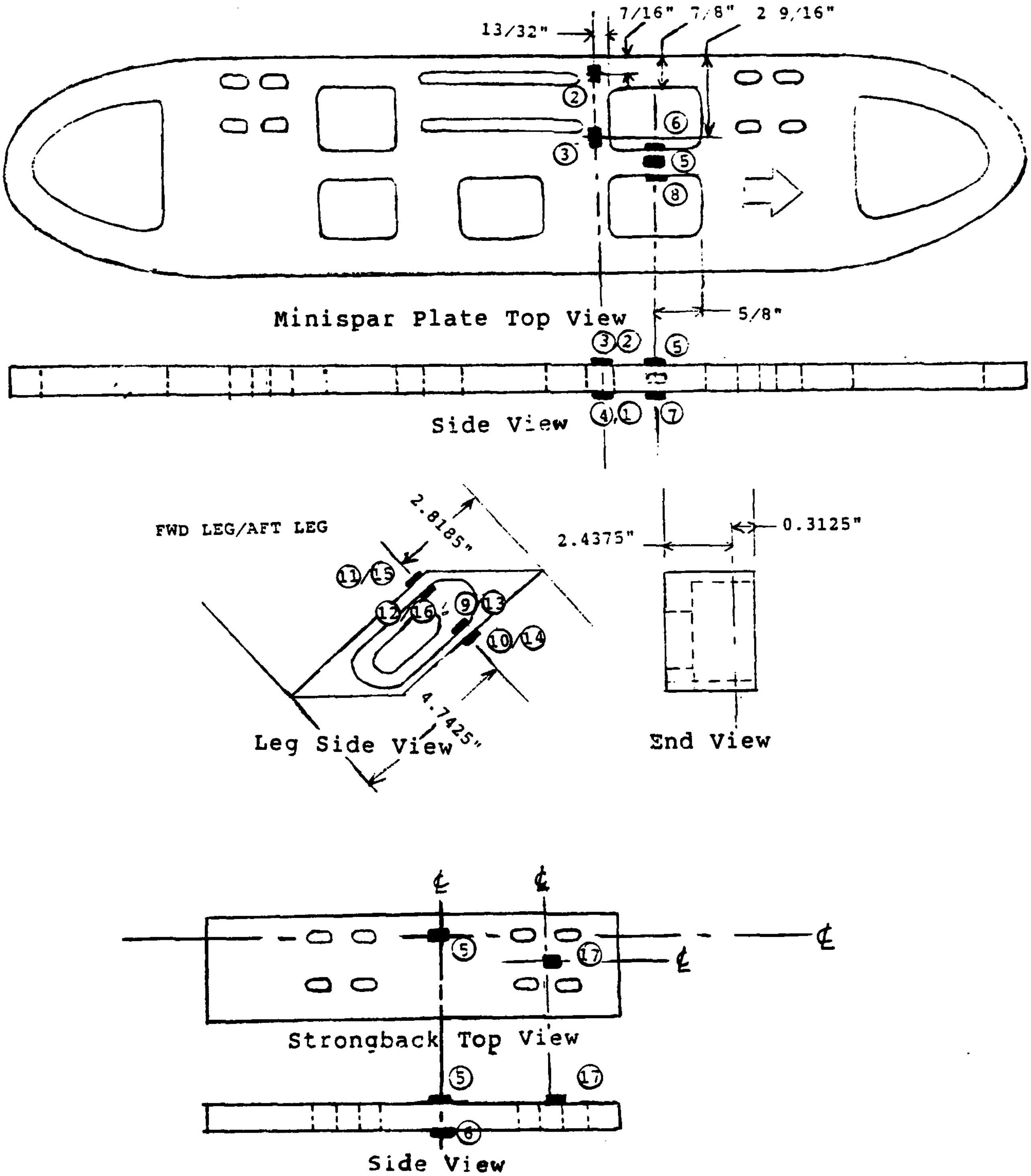


Fig. 9. Locations of strain measurements.

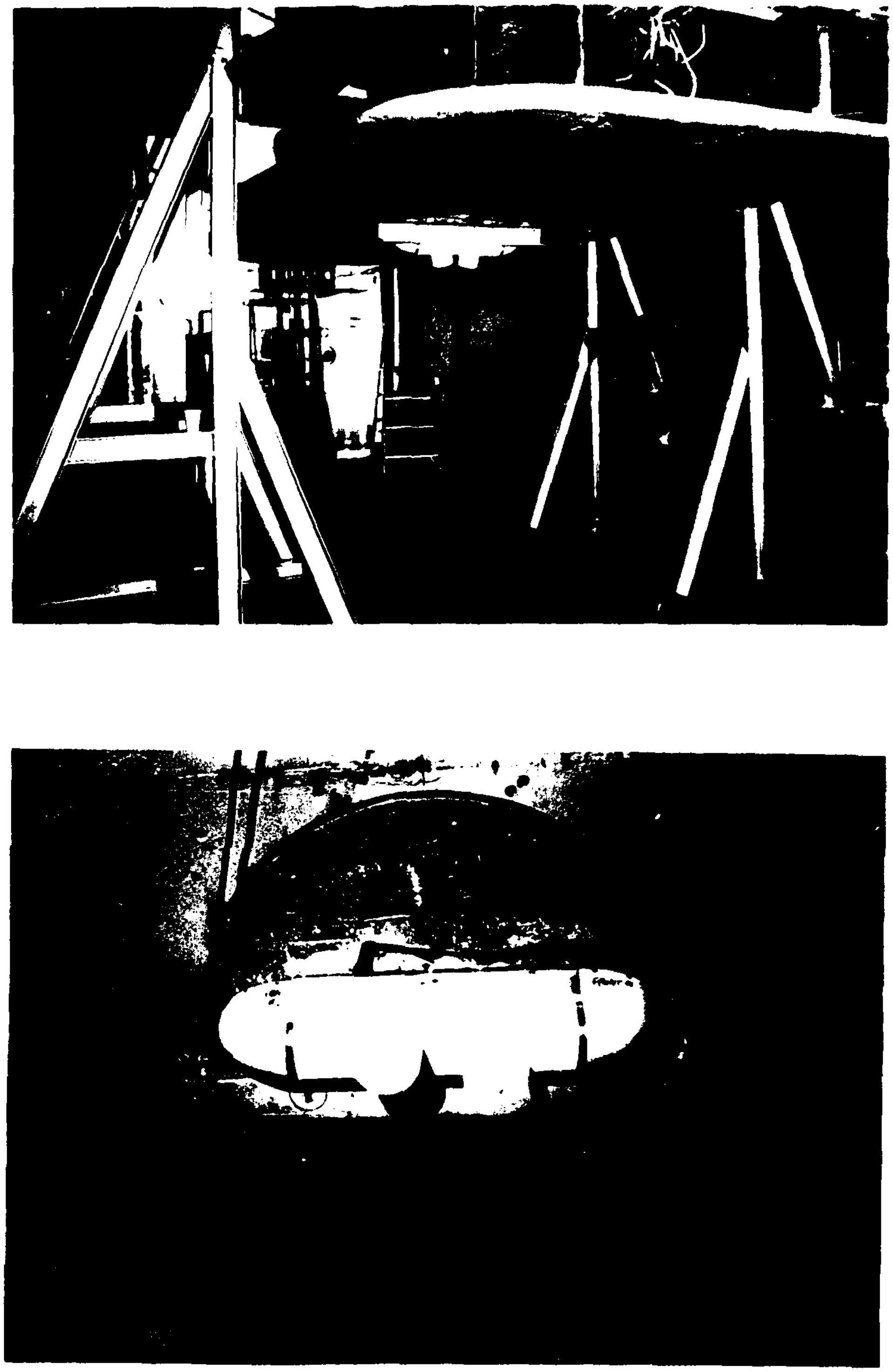


Fig. 10. Pictures of pull test arrangement.

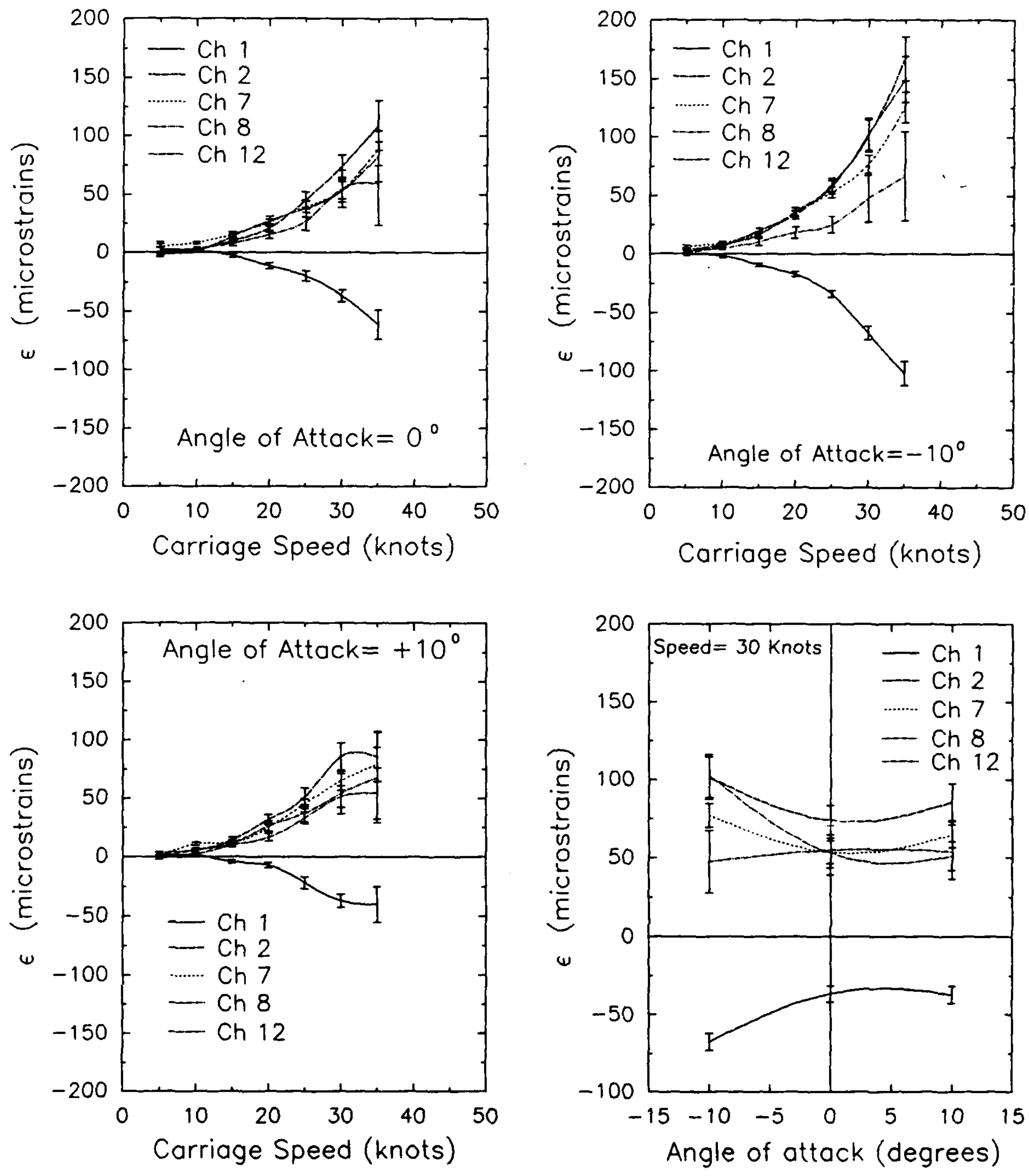


Fig. 11. Plots of carriage test data for Configuration 1.

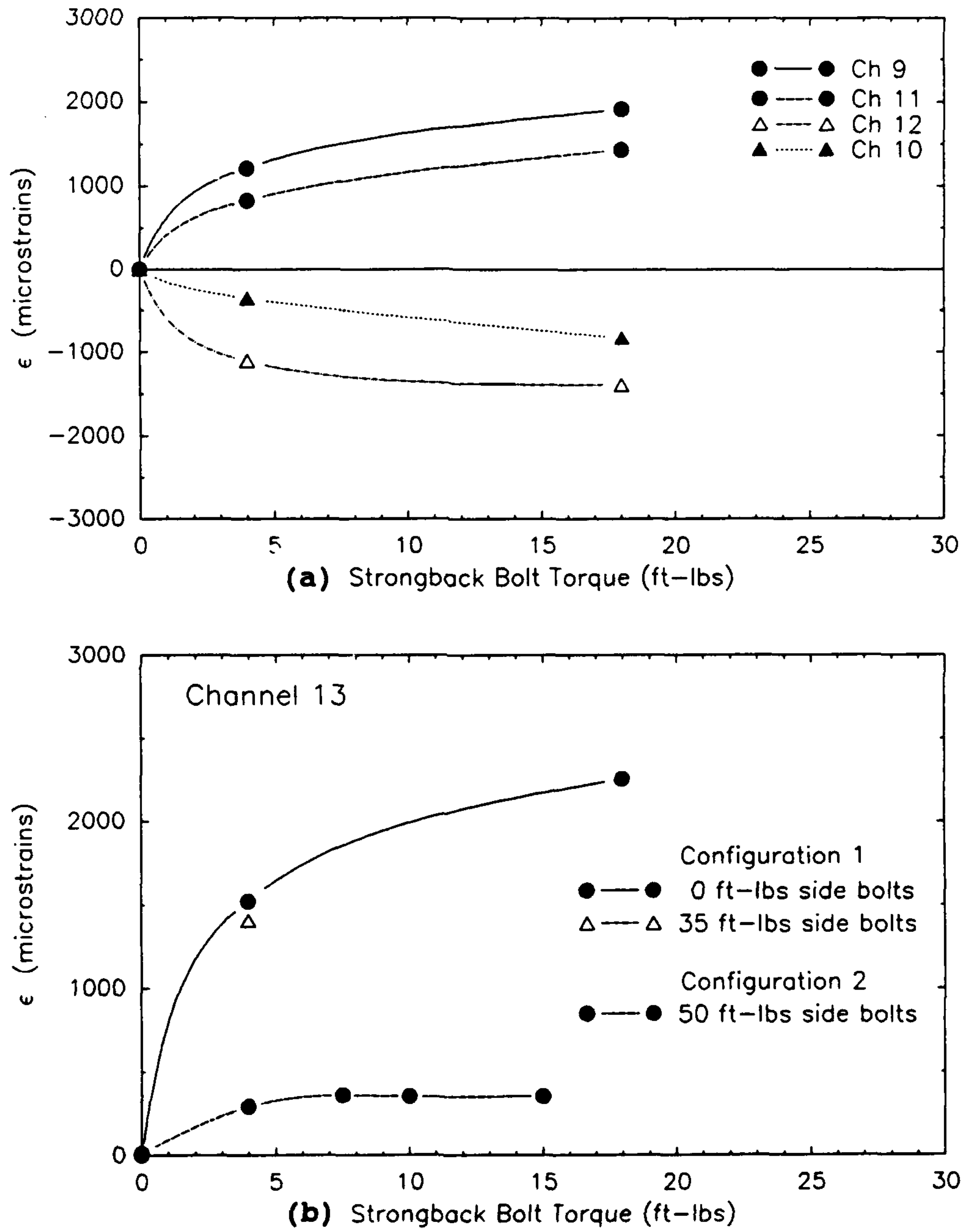
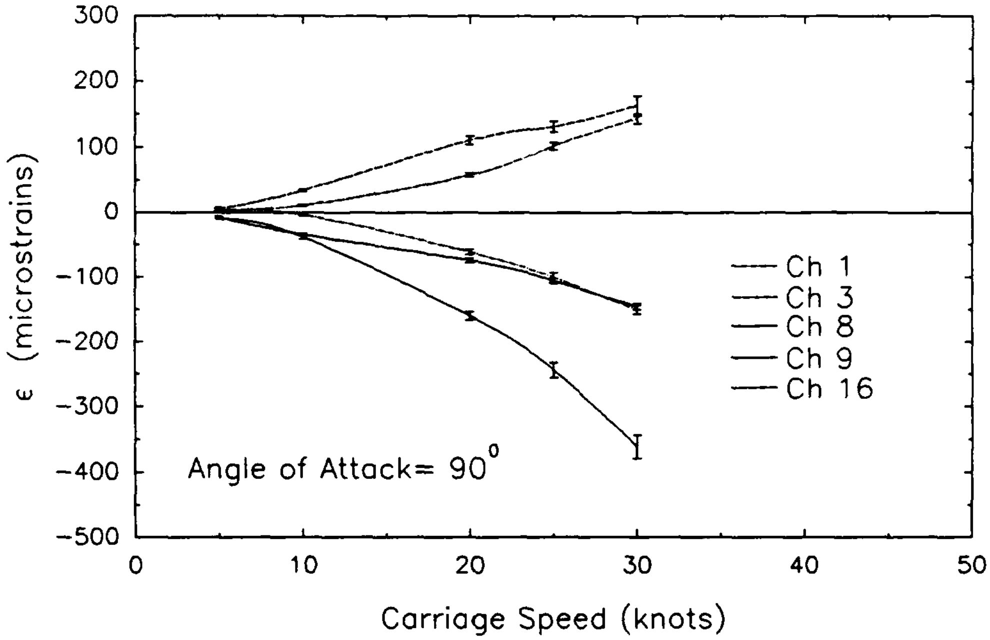


Fig. 12. Torque test plots. (a) Configuration 1 without side bolt torque. (b) Configurations 1 and 2 with side bolt torque.



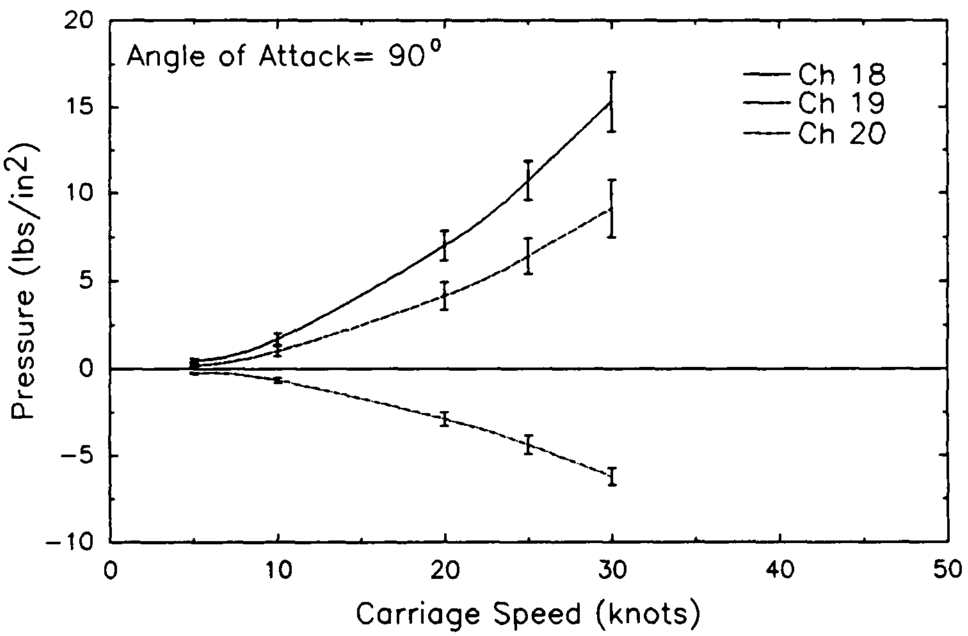


Fig. 13. Plots of carriage test data for Configuration 2.

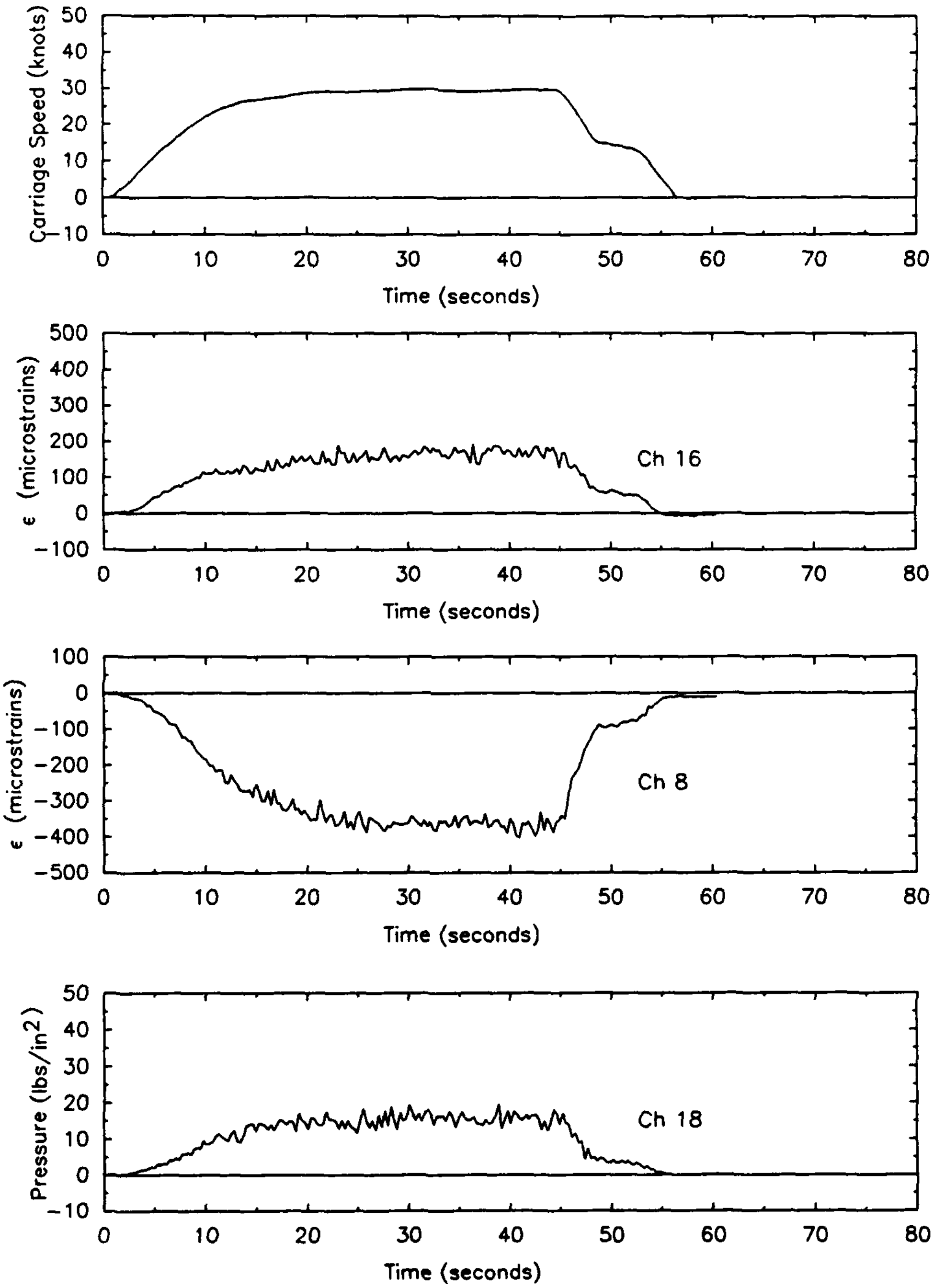


Fig. 14. Real time data for configuration 2.

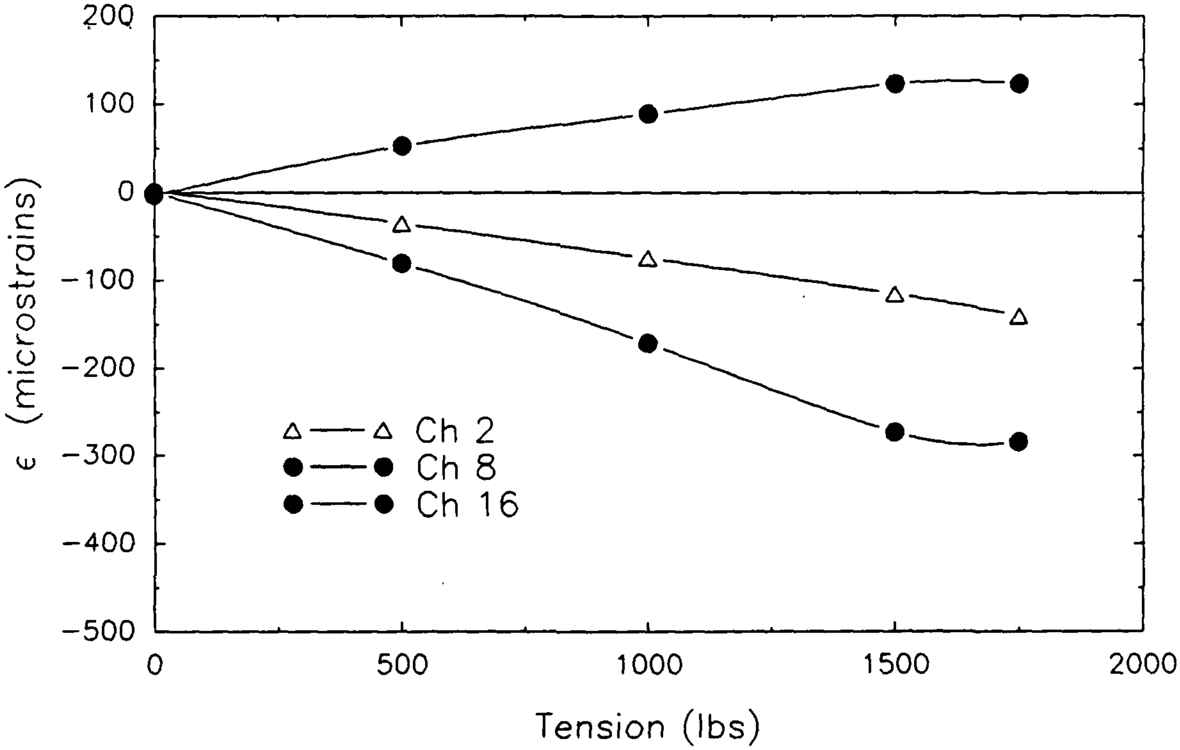


Fig. 15. Pull test graphs.

Table 1. Instrumentation channel lineup.

MEASURAND	LOCATION	CONFIG. #1	#2
STRAIN (10^{-6}in/in)	Minispar Plate, Outside Bottom	1	1
STRAIN (10^{-6}in/in)	Minispar Plate, Outside Top	2	2
STRAIN (10^{-6}in/in)	Minispar Plate, Inside Top	3	3
STRAIN (10^{-6}in/in)	Minispar Plate, Inside Bottom	4	4
STRAIN (10^{-6}in/in)	Minispar Plate, Spindle Top	5	
STRAIN (10^{-6}in/in)	Minispar Plate, Spindle Port	6	
STRAIN (10^{-6}in/in)	Minispar Plate, Spindle Bottom	7	7
STRAIN (10^{-6}in/in)	Minispar Plate, Spindle Starboard	8	8
STRAIN (10^{-6}in/in)	Forward Leg, Inside Forward	9	9
STRAIN (10^{-6}in/in)	Forward Leg, Outside Forward	10	10
STRAIN (10^{-6}in/in)	Forward Leg, Outside Aft	11	11
STRAIN (10^{-6}in/in)	Forward Leg, Inside Aft	12	12
STRAIN (10^{-6}in/in)	Aft Leg, Inside Forward	13	13
STRAIN (10^{-6}in/in)	Aft Leg, Outside Forward	14	14
STRAIN (10^{-6}in/in)	Aft Leg, Outside Aft	15	15
STRAIN (10^{-6}in/in)	Aft Leg, Inside Aft	16	16
VELOCITY (knots)		17	21
STRAIN (10^{-6}in/in)	Strongback, Top Port		5
STRAIN (10^{-6}in/in)	Strongback, Bottom Port		6
STRAIN (10^{-6}in/in)	Strongback, Top Forward		17
PRESSURE (lb/in^2)d	Differential Fwd. to Aft		18
PRESSURE (lb/in^2)a	Forward		19
PRESSURE (lb/in^2)a	Aft		20

Table 2. Matrix of carriage test conditions.

CONFIGURATION (#)	MINISPAR ANGLE (DEGREES)	CARRIAGE SPEEDS (KNOTS)						
		5	10	15	20	25	30	35
1	0	X	X	X	X	X	X	X
1	-10	X	X	X	X	X	X	X
1	10	X	X	X	X	X	X	X
2	90	X	X	X	X	X	X	

APPENDIX A

MDAS 7000 FEATURES

System Processor

68000 microprocessor w/real time, multi-tasking

Built-in FFT and other signal processing routines

Conversion Systems

12-bit resolution for ± 10 volts of signal

625,000 samples per second single channel burst mode rate

200,000 samples per second multi-channel scan rate to RAM

50,000 samples per second to hard disk

Programmable gains and scanning speeds for each channel

Triggering from internal or external sources /pre- and post-triggering sample modes

Storage Systems

40,000,000 byte hard disk

360,000 byte floppy disk

2,000,000 byte RAM memory

I/O Systems

Modular front-end I/O cards for analog and digital signals

Sample and hold circuits

2 to 112 channel capacity

Bridge, thermocouple, optical encoder, stepper motor and filter input cards are available

Other Features

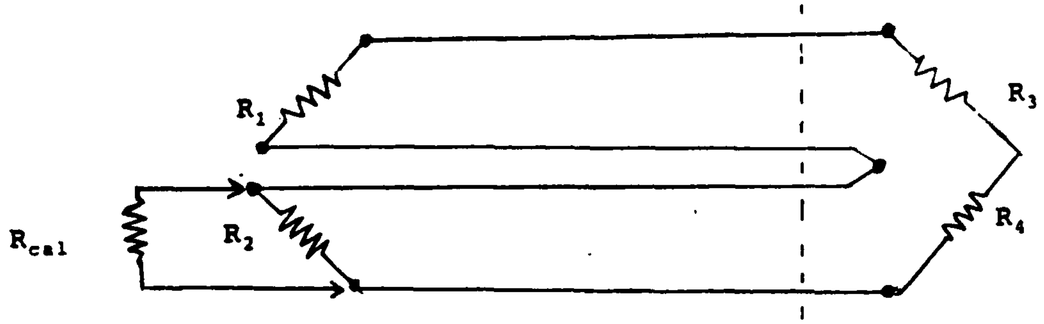
Built-in RS-232, RS-422,and IEEE-488 interfaces

TBASIC PC software

APPENDIX B

CALCULATION OF EQUIVALENT STRAIN FOR SHUNT RESISTOR

The shunt calibration equivalent strain is calculated as follows:



where;

$R_s = R_1 = R_2 = R_3 = R_4 = 350$ ohms

$R_{cal} = 349{,}650$ ohms

$1 / R_p = 1 / R_s + 1 / R_{cal}$

$R_p = R_s \times R_{cal} / (R_s + R_{cal})$

$\Delta R = R_s - R_p$

$\Delta R = (R_s)^2 / (R_s + R_{cal})$

$G.F. = (\Delta R / R) / (\Delta L / L) = 2.13$

$\varepsilon = \Delta L / L$

N = number of active arms = 1

then;

$\varepsilon = (1 / G.F.) \times (1 / N) \times ((R_s / (R_{cal} + R_s))$

$\varepsilon = (1 / 2.13) \times (350 / 350 + 349{,}650)$

$\varepsilon = 469.4 \times 10^{-6}$ in/in

APPENDIX C

EU/VOLT CALCULATION

With a single active arm strain gage the equations relating strain to voltage are shown below;

$$\Delta V \;/\; V_{excit.} = (N \;/\; 4) \times G.F. \times \varepsilon$$

where;

ΔV = change in bridge output voltage

$V_{excit.} \approx 8.0$ volts = bridge excitation voltage

N = the number of active bridge arms

$G.F. = 2.13 = (\Delta R \;/\; R) \;/\; (\Delta L \;/\; L)$ = gage factor

$\varepsilon = 500 \times 10^{-6}$ in/in = strain

then;

$$\Delta V \approx 8.0 \times (1 \;/\; 4) \times 2.13 \times 500 \times 10^{-6}$$

$$\Delta V \approx 2130 \times 10^{-6} \text{ volts} \quad (\text{for } 500\ \mu s)$$

with a gain of 1000;

$$\Delta V \approx 1 \text{ volt} \quad \text{for } 250\ \mu s$$

APPENDIX D
TORQUE TEST DATA

CONFIGURATION #1

Mini-spar	Side	Strong-back	1	2	3	4	5	6	7	8
Torque Values (ft-lb)			Strain Channels: Average Strain and Standard Deviation (microstrains)							
20	0	0	3.0	-2.9	1.1	-0.5	1.7	0.7	1.2	-0.8
			1.7	3.5	2.1	2.4	1.0	0.9	1.4	2.0
20	0	4	131.6	-115.4	13.9	-17.0	6.3	-76.4	86.6	4.1
			2.2	4.1	2.1	2.2	1.4	0.6	1.4	1.4
20	35	4	136.6	-122.9	11.7	-11.6	11.2	-71.8	93.8	11.2
			2.2	2.7	1.8	2.4	1.1	0.8	1.2	1.3
20	0	18	182.7	-178.4	49.5	-44.8	16.4	-79.3	113.5	18.8
			2.2	3.0	1.2	2.1	1.0	1.1	1.2	1.8
0	0	0	2.8	0.9	0.5	-0.5	0.6	-1.3	-0.2	-0.1
			1.6	2.6	1.5	2.1	1.0	0.8	0.8	1.0
20	0	0	2.7	1.6	1.6	4.0	-2.7	9.7	-9.2	4.6
			1.8	3.1	1.6	2.3	1.0	0.6	0.9	1.1
20	35	0	37.9	-13.8	-9.4	13.3	3.1	0.6	2.6	1.9
			1.5	2.7	1.4	2.0	1.2	0.6	0.6	1.0
20	35	4	135.6	-113.1	29.3	-24.8	8.5	-47.5	58.8	5.6
			2.1	2.7	1.5	1.9	1.2	0.5	0.9	1.1

Mini-spar	Side	Strong-back	9	10	11	12	13	14	15	16
Torque Values (ft-lb)			Strain Channels: Average Strain and Standard Deviation (microstrains)							
20	0	0	1.7	-0.3	1.6	0.0	2.2	0.8	1.3	0.0
			0.8	0.3	1.4	1.6	0.5	1.1	1.9	3.8
20	0	4	1208.8	-350.5	823.8	-1105.4	1520.2	-406.4	974.5	-1243.7
			0.8	0.5	1.2	1.5	0.9	0.8	2.1	2.5
20	35	4	1143.4	-363.7	804.7	-1025.9	1419.7	-435.3	938.2	-1250.2
			0.5	0.4	1.5	1.6	0.5	0.8	1.6	2.3
20	0	18	1912.2	-833.0	1431.4	-1393.8	2254.2	-972.8	1981.4	-2015.9
			1.2	0.4	1.3	1.4	1.5	1.0	1.9	2.4
0	0	0	0.4	-0.7	0.9	0.3	1.0	-0.5	2.4	-2.6
			0.8	0.6	1.0	1.4	0.5	1.2	1.2	1.8
20	0	0	15.1	-16.1	-15.1	9.4	-12.1	-12.8	-2.7	30.0
			0.6	0.3	1.2	1.4	0.3	0.6	1.0	1.2
20	35	0	-57.2	-21.2	-59.5	43.5	-29.8	-16.6	-17.2	-25.2
			0.8	0.4	1.2	1.1	0.4	1.0	1.1	1.8
20	35	4	1057.6	-313.0	636.4	-750.1	1405.4	-373.6	878.7	-1139.1
			0.8	0.3	1.1	1.2	0.5	0.8	1.0	1.9

CONFIGURATION #2

Torque Values (ft-lb) Mini-spar	Side	Strong-back	Strain Channels: 1	2	3	4	5	6	7	8	9
			Average Strain and Standard Deviation (microstrains)								
20	0	0	24.0	-18.8	-15.7	17.3	5.4	-8.9	-9.2	3.0	-46.6
			0.4	0.3	0.4	0.4	1.2	1.0	0.4	0.3	0.5
20	50	0	18.9	-14.3	-15.1	17.3	5.8	-8.6	-10.4	1.6	-97.5
			0.5	0.4	0.5	0.4	0.8	1.2	0.4	0.4	0.4
20	50	4	29.6	-23.0	-21.1	20.5	78.9	-88.9	-10.2	4.6	8.8
			0.4	0.3	0.4	0.5	1.0	1.1	0.3	0.3	0.5
20	50	7.5	27.1	-21.1	-19.6	19.9	42.9	-49.8	-10.8	3.9	3.4
			0.5	0.4	0.5	0.5	0.9	1.5	0.4	0.3	0.5
20	50	10	25.9	-20.3	-19.7	20.0	36.7	-46.7	-11.0	3.8	4.4
			0.4	0.5	0.3	0.6	1.1	1.4	0.4	0.3	0.5
20	50	15	24.8	-18.5	-20.2	20.7	33.3	-46.4	-13.5	2.5	15.9
			0.5	0.3	0.5	0.4	1.1	0.9	0.4	0.4	0.4

Torque Values (ft-lb) Mini-spar	Side	Strong-back	Strain Channels: 10	11	12	13	14	15	16	17
			Average Strain and Standard Deviation (microstrains)							
20	0	0	-6.9	-32.9	-6.3	76.5	-48.9	31.9	-122.2	6.9
			0.4	0.2	0.4	0.5	0.5	0.9	0.5	0.7
20	50	0	-0.1	-31.2	14.5	12.6	-49.3	204.1	-58.4	6.6
			0.3	0.4	0.4	0.5	0.5	1.6	0.3	0.8
20	50	4	-152.4	93.6	-71.5	293.7	-152.6	198.2	-154.2	-204.6
			0.4	0.4	0.4	0.6	0.5	1.5	0.5	0.9
20	50	7.5	-143.3	118.2	-63.4	361.5	-145.3	219.6	-271.4	-146.8
			0.3	0.4	0.4	0.4	0.4	1.0	0.5	1.1
20	50	10	-134.9	87.8	-71.4	354.7	-139.3	210.8	-257.9	-122.0
			0.3	0.3	0.4	0.5	0.5	0.6	0.5	0.7
20	50	15	-113.9	30.9	-82.8	355.4	-125.3	186.2	-238.6	-90.2
			0.4	0.3	0.4	0.5	0.4	1.3	0.6	0.9

APPENDIX E
CARRIAGE TEST DATA

Angle of attack = -10 degrees

Ch. No.	Carriage Speed (knots) 5	10	15	20	25	30	35
1	-0.1	-1.6	-9.0	-17.3	-34.0	-67.5	-101.9
	1.2	1.3	1.6	2.1	2.9	5.6	10.4
2	1.5	6.5	20.0	33.7	59.5	101.2	167.2
	1.3	1.4	2.2	3.4	5.7	13.7	18.8
3	3.9	5.4	5.8	13.3	23.9	31.1	41.3
	1.6	1.4	1.4	1.8	2.3	4.7	6.6
4	0.7	-6.1	-8.3	-9.8	-18.6	-19.5	-30.5
	1.0	1.1	1.3	1.5	2.1	4.0	4.0
5	0.6	0.2	-0.0	-0.5	-0.5	-1.5	-0.6
	0.1	0.2	0.2	0.2	0.2	0.2	0.3
6	-10.8	6.7	-9.4	-1.3	-7.7	-6.5	-49.7
	3.9	3.2	3.4	2.7	3.4	4.2	5.3
7	6.2	9.4	17.6	34.8	53.2	77.0	125.8
	1.3	1.4	2.0	2.7	4.5	7.7	13.0
8	4.2	4.9	10.5	18.3	25.3	47.5	66.7
	1.1	1.3	2.9	4.7	7.3	20.0	38.1
9	3.1	0.7	-0.4	2.1	7.9	-6.4	-15.9
	1.6	1.6	1.5	1.9	3.0	8.3	14.5
10	0.3	-2.7	0.6	1.7	5.7	5.2	-1.7
	1.3	1.4	1.4	1.5	1.9	4.7	8.7
11	-2.1	2.5	6.8	5.4	18.1	21.7	45.7
	1.2	1.3	1.5	2.0	2.8	6.5	16.2
12	2.3	7.9	16.3	36.4	57.5	102.4	150.0
	1.4	1.5	2.0	3.3	5.8	13.8	19.6
13	2.3	-0.3	2.0	1.7	2.4	5.7	7.1
	1.8	1.4	1.4	1.3	1.4	1.6	2.2
14	-1.6	0.3	1.1	1.5	4.3	2.2	3.1
	1.5	1.3	1.4	1.2	1.4	2.2	3.0
15	2.6	1.6	-1.5	1.5	0.9	4.6	2.2
	1.9	1.7	1.7	1.6	1.8	1.6	2.5
16	0.1	-1.5	0.3	4.1	8.5	11.4	1.6
	1.3	1.5	1.5	1.6	2.2	3.6	8.5
17	5.1	10.0	15.0	19.8	24.6	29.9	35.4
	0.1	0.3	0.2	0.3	0.2	0.5	0.8

Angle of attack = 0 degrees

Ch. No.	Carriage Speed (knots) 5	10	15	20	25	30	35
1	2.4	1.7	-2.6	-11.1	-20.0	-36.6	-61.1
	5.3	1.1	1.4	2.7	4.4	5.1	12.4
2	0.4	2.3	10.1	21.2	45.1	74.0	109.1
	3.7	1.2	1.9	3.4	7.0	9.4	21.5
3	2.6	3.5	6.6	11.4	12.8	15.5	29.0
	3.3	0.9	1.3	2.1	2.3	3.3	7.7
4	1.4	0.5	-1.9	-4.8	-16.1	-13.2	-24.7
	3.3	1.0	1.1	1.7	1.9	3.0	5.9
5	-0.2	-1.0	-0.3	-0.9	-0.9	-0.7	-0.6
	0.3	0.2	0.3	0.1	0.3	0.1	0.2
6	9.8	7.0	-1.7	-3.8	-5.9	-21.7	-21.4
	14.8	3.7	2.2	4.1	3.2	3.8	6.3
7	4.9	8.5	15.5	26.3	39.3	53.6	89.5
	4.3	0.9	1.9	2.4	5.0	7.3	14.7
8	1.0	3.7	8.0	15.6	27.0	54.8	59.4
	3.6	1.1	2.4	3.6	7.8	15.8	35.5
9	-1.4	-0.3	4.7	5.0	-4.2	-9.5	-24.2
	1.3	2.1	1.6	2.1	3.2	5.8	16.6
10	0.0	-0.4	0.2	0.7	1.2	1.2	-11.4
	1.0	2.0	1.4	1.5	1.7	3.3	7.3
11	1.0	1.6	-0.2	3.0	9.8	5.4	20.1
	0.9	1.3	1.3	1.7	2.8	4.3	13.0
12	-1.1	1.4	13.9	27.2	37.8	53.0	82.9
	0.8	1.4	2.1	4.5	7.3	9.7	21.8
13	1.6	1.5	2.4	2.0	1.2	7.8	13.5
	1.7	1.2	1.2	1.4	1.3	1.6	3.0
14	-1.0	-1.1	-3.6	-3.8	-1.6	-1.4	4.8
	1.4	1.1	1.1	1.1	1.2	1.7	4.2
15	-0.5	0.0	5.7	5.6	0.3	2.4	6.4
	0.8	1.6	1.5	1.5	1.6	1.9	2.2
16	1.0	0.6	-0.2	-1.5	-4.5	-3.1	-6.9
	1.1	1.3	1.4	1.7	2.0	3.2	6.5
17	5.1	9.9	15.2	20.3	25.0	29.8	34.9
	0.1	0.2	0.2	0.5	0.6	0.5	0.9

Angle of attack = +10 degrees

Ch. No.	Carriage Speed (knots) 5	10	15	20	25	30	35
1	0.7	1.7	-4.0	-7.1	-21.9	-37.1	-40.2
	1.1	1.2	1.6	2.0	5.1	5.5	15.0
2	3.1	5.5	14.3	31.8	50.8	85.7	85.7
	1.1	1.4	2.3	4.3	7.6	11.8	21.7
3	1.7	3.2	6.1	9.8	18.6	29.4	43.1
	1.2	1.2	1.2	2.1	2.4	4.9	11.5
4	-2.9	-4.5	-4.8	-6.4	-16.3	-23.9	-36.6
	1.1	1.2	1.2	1.6	2.1	3.5	9.3
5	-0.3	-0.1	-0.2	-0.4	-1.0	-0.9	-0.5
	0.1	0.1	0.2	0.1	0.2	0.2	0.2
6	3.6	0.6	-10.8	-2.5	-6.6	-12.6	-28.1
	3.1	3.8	3.1	3.0	3.6	4.4	8.4
7	-0.3	11.1	12.2	25.0	45.2	64.9	79.3
	1.4	1.3	2.2	3.8	4.2	8.2	14.6
8	2.8	5.8	11.4	26.2	37.1	54.0	67.9
	1.0	1.6	2.8	4.6	7.6	17.4	38.5
9	-2.1	-0.4	2.7	0.4	6.1	-2.0	7.7
	1.6	1.6	1.8	2.2	3.0	7.4	22.2
10	-1.9	-0.6	-3.6	-0.4	0.0	-5.9	-5.6
	1.5	1.5	1.6	1.5	1.9	2.5	8.0
11	2.8	1.8	2.8	7.2	11.8	22.0	27.3
	1.3	1.3	1.5	1.6	2.8	5.2	24.4
12	-0.9	1.9	10.0	16.6	33.1	51.2	54.3
	1.2	1.3	1.7	3.2	5.0	9.2	21.8
13	0.6	1.0	1.4	5.6	3.2	6.6	11.3
	1.2	1.1	1.1	1.2	1.6	2.1	4.4
14	1.1	-2.4	-1.3	-0.4	-3.6	-3.2	1.9
	1.2	1.1	1.2	1.4	1.3	2.0	8.6
15	-1.1	-3.8	5.1	1.8	5.2	9.1	12.7
	1.6	1.8	1.7	1.7	1.6	2.4	4.1
16	0.7	3.1	-1.2	-0.4	-2.8	-3.7	15.9
	1.5	1.4	1.4	1.6	1.9	4.1	15.6
17	5.0	9.9	15.0	20.4	25.1	29.7	35.7
	0.1	0.2	0.2	0.5	0.6	0.5	0.7

Angle of attack = 90 degrees

Ch. No.	Carriage Speed (knots) 5	10	20	25	30
1	1.4	-3.7	-60.8	-100.4	-150.3
	0.9	1.2	3.8	7.0	6.8
.2	-7.2	-10.6	-15.6	-50.7	-80.1
	1.1	1.9	5.6	7.7	12.5
3	5.1	10.9	57.6	102.2	143.5
	0.7	1.2	3.2	6.0	7.2
4	-4.5	-10.3	-45.9	-79.4	-115.0
	0.6	0.8	2.8	5.0	5.1
5	8.8	29.0	-2.9	3.4	44.0
	1.4	1.5	1.7	2.0	3.2
6	-6.9	-0.6	-2.8	-10.5	-14.8
	1.4	1.4	1.9	2.4	3.2
7	3.7	20.1	47.4	77.2	107.1
	1.3	1.8	6.0	8.5	9.4
8	-10.0	-37.9	-159.9	-243.4	-360.8
	1.3	2.7	6.6	11.5	17.8
9	-7.3	-34.2	-73.9	-105.5	-145.5
	1.1	2.2	3.4	3.5	4.8
10	1.8	3.1	1.8	-1.6	-40.4
	0.8	1.1	1.8	2.5	8.4
11	-3.1	-27.1	-68.4	-98.8	-128.1
	0.9	1.6	2.5	3.5	2.9
12	2.8	22.4	52.7	77.0	19.7
	0.9	1.8	3.4	4.9	20.5
13	-2.0	-17.9	-54.2	-47.6	-9.7
	0.9	1.3	3.2	4.6	7.2
14	-0.3	4.6	21.0	20.2	41.1
	0.9	1.1	3.0	3.8	5.9
15	3.7	-6.3	-26.7	-30.4	-25.2
	0.7	1.0	2.1	3.1	5.1
16	6.6	34.0	110.7	131.5	162.7
	1.0	1.9	6.4	8.5	15.2
17	2.9	4.7	10.1	-5.3	-37.6
	1.2	1.3	1.4	2.8	4.3

Ch. No.	Carriage Speed (knots) 5	10	20	25	30
18	0.5	1.7	7.0	10.7	15.3
	0.1	0.3	0.9	1.1	1.8
19	0.2	1.0	4.1	6.4	9.1
	0.1	0.3	0.8	1.0	1.6
20	-0.3	-0.7	-2.9	-4.4	-6.2
	0.0	0.1	0.4	0.5	0.5
21	5.1	9.9	19.9	24.7	29.4
	0.3	0.2	0.2	0.3	0.3

APPENDIX F

PULL TEST DATA

Tension (lb)	ch1	ch2	ch3	ch4	ch5	ch6	ch7	ch8	ch9	ch10	ch11	ch12	ch13	ch14	ch15	ch16	ch17
0	1.7	2.2	1.9	-1.4	20.1	-3.0	1.6	-0.1	1.1	-2.1	2.1	-3.2	2.5	-1.8	-1.7	-3.3	2.1
	0.6	0.6	1.0	0.8	1.6	2.1	1.2	0.6	0.9	1.1	0.8	0.8	0.9	1.1	1.1	0.9	1.1
500	-12.8	-35.2	10.6	-8.9	16.7	-2.6	7.4	-80.5	-56.8	9.5	-40.4	40.9	-22.2	17.6	-13.1	52.9	7.5
	0.7	0.8	0.9	0.7	1.8	1.9	0.8	0.6	1.0	0.8	1.0	0.8	1.3	1.1	1.2	0.8	1.1
1000	-39.4	-74.4	24.8	-20.4	15.3	-3.4	9.4	-171.3	-69.4	14.3	-58.2	53.3	-40.1	25.9	-21.0	89.1	9.6
	1.0	1.1	0.8	0.7	2.3	1.8	0.8	0.9	1.1	0.9	1.0	1.0	1.4	1.1	1.0	0.8	1.3
1500	-72.3	-114.9	37.8	-30.9	16.3	-1.8	8.4	-273.1	-88.9	17.5	-73.3	73.7	-52.4	32.3	-23.9	123.2	6.8
	2.0	3.5	1.5	1.2	1.9	1.9	1.0	6.9	1.8	0.8	1.6	1.6	1.2	0.8	1.0	2.8	1.0
1750	-74.9	-139.9	39.2	-34.1	-0.1	-7.7	8.3	-284.0	-86.2	15.7	-71.1	74.8	-46.9	38.2	-21.7	123.7	3.7
	1.3	1.3	0.8	1.0	2.7	1.9	1.3	0.2	1.4	1.4	1.6	1.4	2.1	1.8	2.2	1.8	1.4

APPENDIX G

ARMCO NITRONIC 50 STEEL INFORMATION[4]

Since;

σ = 55,000 psi (0.2 % Minimum Yield Strength)

$E = 28.9 \times 10^6$ = (Modulus of Elasticity in Tension)

ε = strain

then;

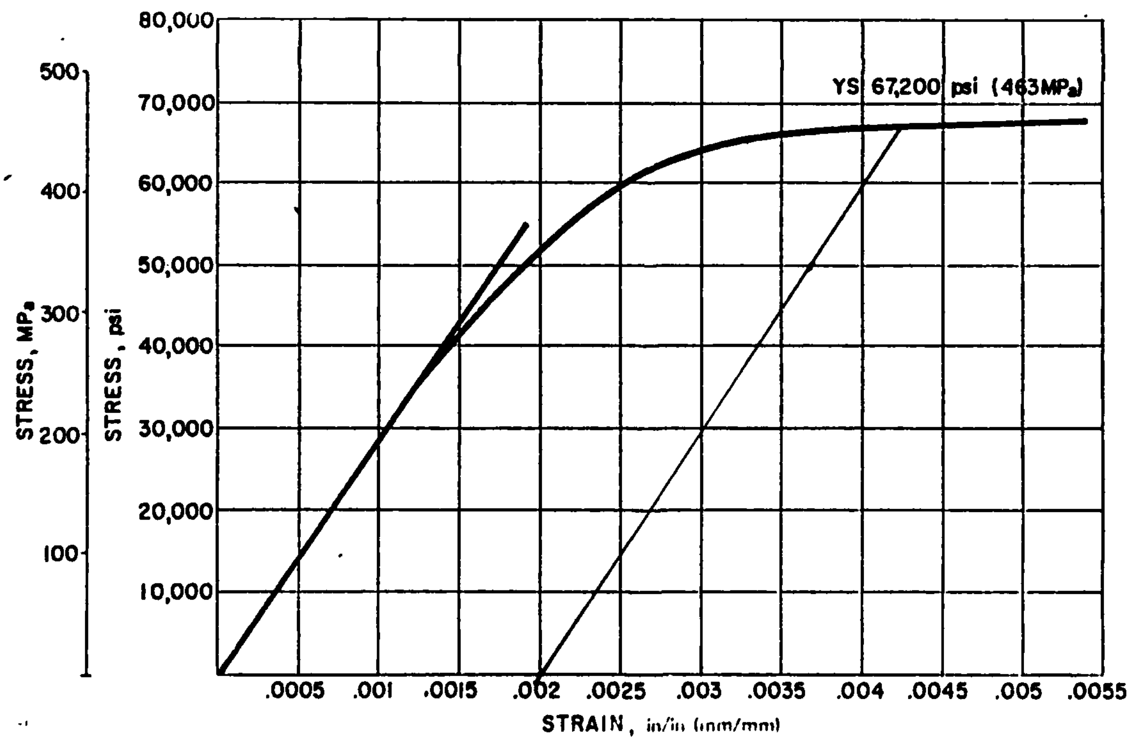
$E = \sigma / \varepsilon$

$\varepsilon = \sigma / E$

$\varepsilon = 55{,}000 / 28.9 \times 10^6$

$\varepsilon = 1900 \times 10^{-6}$ in/in = 1900 μin/in

STRESS-STRAIN CURVE (LONGITUDINAL)



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